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Design of Superelevation of Highway Curves: An Overview and Distribution Methods

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Abstract Superelevation is the banking of highway horizontal curves to assist the driver by counteracting the lateral acceleration produced by tracking the curve. Superelevation is expressed as a decimal, representing the ratio of the pavement slope to width, and ranging from 0.04 to 0.12. Proper superelevation allows a vehicle to safely turn at high speeds and will make riders comfortable. Centrifugal force is the outward pull on a vehicle traversing a horizontal curve. As a vehicle traverses a horizontal curve, centrifugal force is counter-balanced by the vehicle weight component due to roadway superelevation and by the side friction between tires and surfacing. Excessive centrifugal force may cause considerable lateral movement of the turning vehicle and it may become very hard to stay inside the driving lane. Superelevation and side friction are the two factors that help stabilize a turning vehicle. Inadequate superelevation can cause vehicles to skid as they travel through a curve, resulting in a run-off-road crash. Trucks and other large vehicles with high centers of mass are more likely to roll over at curves with inadequate superelevation. There are practical limits to the rate of superelevation. High rates create steering problems for drivers traveling at lower speeds, particularly during ice or snow conditions. This paper presents an overview of the concept of highway superelevation, and AASHTO distribution methods that utilize both side friction and superelevation in the design of the highway horizontal alignments.

Keywords: *superelevation, banking of highway curves, horizontal alignments, circular curves, spiral curves*

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1. Introduction

The operation of a highway is directly affected by its horizontal and vertical alignments. The alignments, in turn, will affect vehicle operating speeds, sight distances, and highway capacity [1-7]. The horizontal alignment consists of straight roadway sections (tangents) connected by horizontal curves, which are normally circular curves with or without transition (spiral) curves. The design of a horizontal alignment is influenced by many factors including terrain functional classification, design speed, traffic volume, right-of-way, environmental conditions, and the required level of service. The horizontal alignment must adhere to specific design criteria such as minimum radii, superelevation rates, and sight distance. These criteria will maximize the overall safety of the roadway and enhance the aesthetic appearance of the highway [8-18]. The horizontal alignment of a highway allows for a smooth transition between the tangents or straight sections. Circular curves and spirals are the most common types of horizontal curves used to meet the standard design criteria. A circular curve is a curve with a constant radius connecting two tangents. A compound curve is composed of two or more adjoining circular curves of different radii. The centers of the arcs of the compound curves are located on the same side of the alignment. The combination of a short length of tangent between two circular curves is referred to as a broken-back curve. A reverse curve consists of two adjoining circular curves with the curve centers located on opposite sides of the alignment. Spiral curves are used in horizontal alignments to provide a gradual transition between tangent sections and circular curves. While a circular curve has a radius that is constant, a spiral curve has a radius that varies along its length. The radius decreases from infinity at the tangent to the radius of the circular curve that is intended to meet. A vehicle entering a curve must transition from a straight line to a fixed radius. To accomplish this, the vehicle travels along a path with a continually changing radius. Consequently, a spiral will more closely provide the natural path of the turning vehicle [1-9].

Centrifugal force is the outward pull on a vehicle traversing a horizontal curve. When traveling at low speeds or on curves with large radii, the effects of centrifugal force are minor. However, when travelling at higher speeds or around curves with smaller radii, the effects of centrifugal force increase. If not adequately controlled, the centrifugal force may cause considerable lateral movement of the turning vehicle and it may become impossible to stay inside the driving lane. Superelevation and side friction are the two factors that keep stabilize a turning vehicle. Superelevation is the

banking of the roadway such that the outside edge of pavement is higher than the inside edge. The use of superelevation allows a vehicle to travel through a curve more safely and at a higher speed than would otherwise be possible. Side friction developed between the tires and the road surface also acts to counterbalance the outward pull on the vehicle. The transitional rate of applying superelevation into and out of curves is affected by several factors. These factors include design speed, curve radius, and number of travel lanes. Minimum curve radii for a horizontal alignment are determined by the design speed and superelevation rate. Higher design speeds require more superelevation than lower design speeds for a given radius [11-15]. Obviously, sharper curves require more superelevation than flatter curves for a given design speed.

2. The Rates of Superelevation (e)

According to the laws of mechanics, when a vehicle travels on a curve it is forced outward by centrifugal force. The purpose of superelevation or banking of curves is to counteract the centripetal acceleration produced as a vehicle rounds a curve. The purpose of superelevation or banking of curves is to counteract the centripetal acceleration produced as a vehicle rounds a curve. On a superelevated highway, the centrifugal force is resisted by the vehicle weight component parallel to the superelevated surface and side friction between the tires and pavement. It is impractical to balance centrifugal force by superelevation alone, because for any given curve radius a certain superelevation rate is exactly correct for only one driving speed. At all other speeds there will be a side thrust either outward or inward, relative to the curve center, which must be offset by side friction. If the vehicle is not skidding, these forces are in equilibrium. When a vehicle travels at constant speed on a curve superelevated so that the f value is zero, the centripetal acceleration is sustained by a component of the vehicle's weight only and, theoretically, no steering force is needed. A vehicle traveling faster or slower than the balance speed develops tire friction as steering effort is applied to prevent movement to the outside or to the inside of the curve. On non superelevated curves, travel at different speeds is also possible by utilizing appropriate amounts of side friction to sustain the varying lateral acceleration [1-7].

The maximum superelevation for a section of roadway is dependent on climatic conditions, and type of terrain. Roadways in rural areas are typically designed with a maximum superelevation rate of 8 percent. In mountainous areas, a maximum superelevation rate of 6 percent is used due to the increased likelihood of ice and snow. Urban roadways are normally designed with a maximum superelevation rate of 4 percent. In many cases, superelevation in urban areas may be completely eliminated, because it could interfere with drainage systems, utilities, and pavement tie-ins at intersecting streets and driveways [1-5]. AASHTO Greenbook (2011) recommends that maximum superelevation rates be limited to 12 percent for rural roadways without ice; 8 to 10 percent for rural roadways for which snow or ice are likely to be present; and 6 percent or 4 percent for urban and suburban streets [1].

3. Effects of Grades on Superelevation Rates

On long steep grades, drivers tend to travel faster in the downgrade than in the upgrade direction. Research has shown that the side friction demand is greater on both downgrades (due to braking forces) and steep upgrades (due to the tractive forces). Some adjustment in superelevation rates should be considered for grades steeper than 5 percent. In the case of a divided highway with each roadway independently superelevated, or on a one-way ramp, such an adjustment can be readily made. AASHTO superelevation tables can be used directly by assuming a slightly higher design speed for the downgrade. Since vehicles tend to slow on steep upgrades, the superelevation adjustment can be made without reducing the design speed for the upgrade. On two-lane and multilane undivided roadways, the adjustment for grade can be made by assuming a slightly higher design speed for the downgrade and applying it to the whole traveled way (both upgrade and downgrade sides). The added superelevation for the upgrade can help counter the loss of available side friction due to tractive forces [1-6].

4. Analysis of Superelevation (e) and Side Friction (f)

When moving on a circular path, a vehicle is subject to centrifugal force that acts away from the center of the curve. Vehicle weight, roadway superelevation, and side friction between the tires and the roadway counterbalance this force as shown in Figure 1.

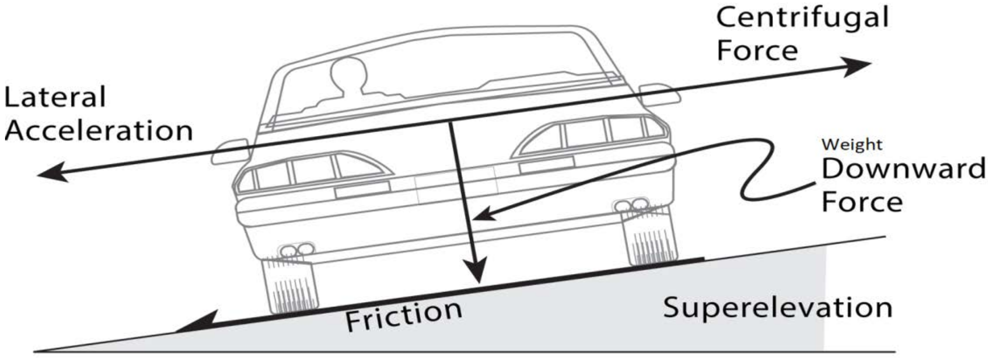

Figure 1. Highway Superelevation Scheme

If the vehicle is not skidding, all forces are in equilibrium as the following equation represents [8,11-18]:

$$\frac{0.067V^2}{R} = \frac{V^2}{15R}$$

$$e + f = \frac{v^2}{gR} = \frac{0.067V^2}{R} = \frac{V^2}{15R}(\text{U.S. Customary})$$

$$e + f = \frac{v^2}{gR} = \frac{0.0079V^2}{R} = \frac{V^2}{127R}(\text{Metric})$$

Where
e=rate of superelevation, ft/ft (m/m)
f=side friction factor
v=vehicle speed, ft/s (m/s)
V=vehicle speed, mph (km/h)
g=gravitational constant 32.2 ft/s^2 (9.81m/s^2)
R=radius of curve, ft (m).

5. Side Friction Factor (f)

The side friction factor to counter centrifugal forces is reduced by vehicle decelerating and accelerating. However, the Antilock Braking Systems (ABS) have greatly improved this aspect. The friction factor also depends on other variables, including the vehicle speed, weight, suspension, tire condition (wear, tire pressure, tire temperature), tire design (tread, contact patch, rubber compound, sidewall stiffness), pavement, and any substance between the tire and pavement. The side-friction factor has practical upper limits. In every case, the side-friction factor that is used in design should be well below the side-friction factor of impending release. In addition to the safety concerns, drivers don't feel comfortable if the roadway seems to rely heavily on the frictional force. The upper limit of this factor is that at which the tire is skidding or at the point of impending skid. Because highway curves are designed to avoid skidding conditions with a margin of safety, the f values should be substantially less than the coefficient of friction of impending skid. The side friction factor at which skidding is imminent depends on a number of factors, such as the speed of the vehicle, the type and condition of the roadway surface, and the type and condition of the tires. Different research has recorded different maximum rates at the same speeds for similar composition pavements, because of the inherent differences in pavement texture, weather conditions, and tire condition [1-9]. In general, studies show that there is a decrease in friction values for an increase in speed. In selecting the maximum allowable side friction factors for use in design, one criterion is the point at which the centrifugal force is sufficient to cause the driver to experience a feeling of discomfort and cause him or her to react instinctively to avoid higher speed. The speed on a curve, at which discomfort due to centrifugal force is evident to the driver, can be accepted as a design control for the maximum allowable amount of side friction.

6. Design of Superelevation and Side Friction Factor (How to Select e and f)

The following steps describe the design of superelevation [8-15]:

STEP 1: Calculate the superelevation € for the highway using the specified design speed and neglecting the friction factor, i.e. f = 0.

STEP 2: If the calculated value (e) is less than the limiting value of (e) for the highway being considered (i.e. max e for the highway), then use the obtained value. If it exceeds max e, then use the limiting value of e (i.e. max e) and proceed to the next step.

STEP 3: Check the side friction factor (f) developed for the maximum value of (e) at the full value of design speed, If the value of f thus calculated is less than max f, then the super elevation obtained in step 2 is safe for the design speed. If not, calculate the restricted speed again.

STEP 4: If the calculated value of (f) exceeds the max f allowed for the highway, then recalculate the design speed so that the speed of the vehicles is restricted to the value obtained by allowing the limiting values of (e) and (f) together.

NOTE: it is always desirable to design the road without speed restriction at curves. Hence, the curve should be realigned, if possible, with a longer radius of curvature so that the design speed can be maintained without any restriction.

7. AASHTO Distribution Methods of e and f

For a given design speed, AASHTO Greenbook (2011) lists five methods for sustaining lateral acceleration on curves by use of e or f, or both, as follows [1,10]:

Method 1:

Superelevation and side friction are directly proportional to the inverse of the radius (i.e., Superelevation (e) and side friction (f) are increased linearly as the radius decreases).

The straight-line relationship between superelevation and the inverse of the radius of the curve in this method results in a similar relationship between side friction and the radius for vehicles traveling at either the design or average running speed. This method has considerable merit and logic in addition to its simplicity. This method might appear to be an ideal means of distributing the side friction factor, but its appropriateness depends on travel at a constant speed by each vehicle along the road. Method 1 is expressed mathematically as [1,10]:

$$e_1 = \frac{R_{\min}}{R} e_{\max};$$

$$f_1 = \frac{v^2}{gR} - \frac{R_{\min}}{R} e_{\max}; \left(R_{\min} \le R \le \infty\right)$$

Method 2:

Side friction is such that a vehicle traveling at design speed has all lateral acceleration sustained by side friction on curves up to those designed for max f. For sharper

curves, f remains equal to max f and superelevation is then used to sustain lateral acceleration until (e) reaches max e. In this method, first (f) and then (e) are increased in inverse proportion to the radius of curvature. Hereby, superelevation is introduced only after the maximum side friction has been used. Therefore, no superelevation is needed on flatter curves that need less than maximum side friction for vehicles traveling at the design speed. This method is particularly appropriate on low-speed urban streets where, because of various constraints, superelevation frequently cannot be provided. Method 2 is mathematically expressed by the following [1,10]:

$$e_2 = \frac{v^2}{gR} - f_{\max};\ f_2 = f_{\max};\left(R_{\min} \le R \le R_{fo}\right)$$

$$e_2 = O;\ f_2 = \frac{v^2}{gR};\left(R_{fo} \le R \le \infty\right).$$

Method 3:

Superelevation is such that a vehicle traveling at the design speed has all lateral acceleration sustained by superelevation on curves up to those designed for max e. For sharper curves, (e) remains at max e and side friction is then used to sustain lateral acceleration until f reaches its max value. In this method, first (e) and then (f) are increased in inverse proportion to the radius of curvature. This method was practiced many years ago and requires that superelevation to sustain all lateral acceleration for a vehicle traveling at the design speed up maximum practical superelevation. Under this method, no side friction is provided on flat curves with less than maximum superelevation. For vehicles traveling at average running speed, this superelevation method results in negative friction for curves of very flat radii. Method 3 is expressed mathematically as follows [1,10]:

$$\grave{}\ e_3 = e_{\max};\ f_3 = \frac{v^2}{gR} - e_{\max};\left(R_{\min} \le R \le R_{eo}\right)$$

$$e_3 = \frac{v^2}{gR};\ f_3 = 0;\left(R_{eo} \le R \le \infty\right)$$

Method 4:

This method is the same as Method 3, except that it is based on average running speed instead of design speed. This method has been used with an average running speed for which all lateral acceleration is sustained by superelevation of curves flatter than that needing the maximum rate of superelevation. It utilizes superelevation at lower speeds than that of design speed. Method 4 is expressed mathematically in the same manner as of method 3 using running speed instead of design speed [1,10]:

$$e_3 = e_{\max};\ f_3 = \frac{v^2}{gR} - e_{\max};\left(R_{\min} \le R \le R_{eo}\right)$$

$$e_3 = \frac{v^2}{gR};\ f_3 = 0;\left(R_{eo} \le R \le \infty\right)$$

Method 5:

Superelevation and side friction are in a curvilinear relation with the inverse of the radius of the curve, with values between those of Methods 1 and 3. In this method, superelevation along with side friction has a curvilinear relationship with the inverse of the curve radius, within values between that for Methods 1 and 3. Method 5 utilizes a method of curvilinear distribution that depends upon the unsymmetrical parabolic curve of distribution of f. Method 5 is expressed mathematically as follows [1,10]:

$$R_{PI} = \frac{V^2}{ge_{\max}}$$

$$f_5 = f_{\max}\frac{R_{\min}R_{PI}}{2R^2};1/R \le 1/R_{PI}$$

$$f_5 = f_{\max}\left[\begin{array}{l}\frac{R_{\min}}{R}\left(\frac{R_{PI}-R}{R_{PI}-R_{\min}}\right)\\ +\frac{R_{\min}R_{PI}}{2R^2}\left(\frac{R-R_{\min}}{R_{PI}-R_{\min}}\right)^2\end{array}\right];\ 1/R > 1/R_{PI}$$

$$e_5 = \frac{v^2}{gR} - f_5.$$

AASHTO recommends using Method 2 for low speed urban roadways, since it relies first on side friction, then on superelevation to control lateral acceleration. Drivers are willing to accept more discomfort on low speed urban roadways due to the anticipation of more critical conditions [1-5]. In addition, several factors make it difficult, if not impossible, to apply superelevation to urban roadways, including:

- Frequency of cross streets and driveways.
- Vehicles stopping on curves at signalized intersections.
- Meeting the grade of adjacent properties.
- Surface drainage.
- Pedestrian ramps.
- Wider pavement area.

AASHTO recommends using Method 5 for determining the distribution of superelevation and side friction for high speed roadways (rural and urban), because superelevation is progressively added as speed increases. It also works well for turning roadways such as ramps [1-5].

For urban streets with design speeds of 50 km/h (30 mph) or less, superelevation is rarely necessary. Most of the time, the side friction factor is adequate. If the maximum allowable friction factor is exceeded, consider doing the following activities [1]:

1. Do not use superelevation on curves if it would increase drainage problems.
2. Make sure to meet the grades of the surrounding properties, entrances, and cross streets without introducing grades on the main roadway that exceed the maximum longitudinal grade.
3. Supply sufficient area to properly transition to and from the desired superelevation.
4. Weigh the use of superelevation and the attainable design speed against the construction effort and the local municipal practice.

8. Methods of Attaining Superelevation

AASHTO Greenbook (2011) presents four methods to transition the pavement to a superelevated cross section [1]:

(1) Revolving a traveled way with normal cross slopes about the centerline profile,

(2) Revolving a traveled way with normal cross slopes about the inside-edge profile,

(3) Revolving a traveled way with normal cross slopes about the outside-edge profile,

(4) Revolving a straight cross slope traveled way about the outside-edge profile.

The method of rotation about the centerline is usually the most adaptable. On the other hand, the method of rotation about the inside edge is preferable where the lower edge profile is a major control, as for drainage. Where the overall appearance (aesthetic) is a high priority, the methods of rotation about the outer side edge are desirable because the upper-edge profile retains the smoothness of the road profile.

9. Superelevation Transition Design

The design of transition sections includes consideration of transitions in the roadway cross slope and possible transition curves incorporated in the horizontal alignment. The former consideration is referred to as superelevation transition and the latter is referred to as alignment transition. The superelevation transition section consists of the superelevation runoff and tangent runout sections. The superelevation runoff section consists of the length of roadway needed to accomplish a change in outside-lane cross slope from zero to full superelevation, or vice versa. The tangent runout section consists of the length of roadway needed to accomplish a change in outside-lane cross slope from the normal cross slope rate to zero, or vice versa. To limit lateral acceleration, the pavement rotation in the superelevation transition section should be achieved over a length that is sufficient to make such rotation convenient to drivers. To be pleasing in appearance, the pavement edges should not appear distorted to the driver. When a transition curve is not used, the roadway tangent directly adjoins the main circular curve. This type of transition design is referred to as the “tangent-to-curve” transition [1-7].

10. Placing Superelevation Transition

How superelevation transition is placed is critical to driver safety and comfort. If all the superelevation transition is placed in the curve, the lateral acceleration the driver experiences upon entering the curve may be intolerable. In addition, side friction may not be sufficient to prevent the vehicle from skidding off the road. Two methods for overcoming these problems are:

1. Place superelevation transition in a transition spiral curve, or

2. If a spiral curve is not used, place a portion of the superelevation transition in the tangent, and the rest in the horizontal curve.

If a spiral curve is not used, 2/3 of the superelevation runoff length is developed on the tangent section of the roadway, and 1/3 developed on the circular curve. Where spiral transition curves are used, the full length of the spiral is equal to the superelevation runoff [11-20].

11. Conclusion

Superelevation is the banking of the roadway along a horizontal curve so motorists can safely and comfortably maneuver the curve at reasonable speeds. Superelevation is provided to counteract the effect of centrifugal force and to minimize the tendency of the vehicle to overturn or skid by raising the outer edge of pavement with respect to the inner edge, providing a transverse slope throughout the length of the horizontal curve. High rates of superelevation may cause slow moving vehicles to slide down the banking in snow and ice. High superelevation rates can be difficult to attain in urban settings due to closely spaced intersections, driveways, and limited right of way. Maximum superelevation rates are chosen to limit the adverse effects of superelevation. AASHTO recommends the following maximum superelevation rates:

• Maximum superelevation rates of 4% and 6% are for urban areas.

• Maximum superelevation rates of 6% and 8% are for areas that have frequent ice and snow.

• Maximum superelevation rates of 10% and 12% in rural areas without ice or snow concerns

Friction allows cornering, braking, and acceleration forces to be transmitted from the tires to the pavement. Rather than using the “coefficient of friction” from dynamics, highway engineers use a ratio of the lateral forces that the pavement can resist. This lateral ratio is most commonly referred to as the “side friction factor.” AASHTO Green Book presents five methods for distributing superelevation and side friction factor as described below:

1. Superelevation (e) and side friction (f) are increased linearly as the radius decreases.

2. Superelevation is minimized so that a vehicle traveling at the design speed has all the lateral acceleration sustained by side friction until the side friction is at the maximum.

3. Superelevation is increased so that a vehicle traveling at the design speed has all lateral acceleration sustained by superelevation until the superelevation is at its maximum.

4. This method is the same as method 3, except that it is based on average running speeds instead of design speed.

5. This method uses values between methods 1 and 3 so that extra superelevation is provided for curves with radii above the minimum radius (i.e., intermediate curves).

For low speed facilities, AASHTO recommends method 2 since it minimizes the disturbance of superelevation to adjacent property in urban areas, closed drainage systems, low speed operations, and intersections. For high speed facilities, AASHTO recommends method 5.

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